

AD-A135818

# TECHNICAL LIBRARY

AD

AD-E401 112

TECHNICAL REPORT ARLCD-TR-83048

## THEORETICAL CALCULATIONS OF H(2) CARS SPECTRA FOR PROPELLANT FLAMES

JOANNE FENDELL  
L. E. HARRIS  
KENNETH ARON

DECEMBER 1983



**U.S. ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER**

**LARGE CALIBER WEAPON SYSTEMS LABORATORY**

**DOVER, NEW JERSEY**

**APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.**

The views, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

Destroy this report when no longer needed. Do not return to the originator.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

DD FORM 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

## 20. ABSTRACT (cont)

For this particular case, the calculations of interest are for the observed S- and Q-branch transitions of H(2) for  $v$  equal to 0 and 1. Spectroscopic constants available in the literature and the results of an ab initio calculation performed by Ermler were used in the analysis.

Ermler used the potential energy curves for the ground state of hydrogen calculated by Kolos and Wolniewicz over a range of  $0.4 \leq R \leq 10.0$  a.u. as the basis for this calculation. The result is a set of spectroscopic constants superior to any other set examined.

Having assigned the transitions, the third order susceptibility, which gives a model for data reduction of CARS spectra can be calculated. Temperature and concentration for a given species can be obtained by comparing the theoretical spectra with experimental results.

## ACKNOWLEDGMENT

The authors would like to thank Professor W. C. Ermler, Stevens Institute of Technology, for providing us with the ab initio calculations and helpful discussions.

## CONTENTS

	Page
Introduction	1
CARS Theory	1
Results	2
Spectroscopic Constants	2
Application of Spectroscopic Constants	2
Calculation of H <sub>2</sub> CARS S- and Q-Branched	3
Discussion	4
References	5
Distribution List	15

## TABLES

	Page
1 Comparison of spectroscopic constants (cm <sup>-1</sup> )	7
2 Calculation of selected transitions (cm <sup>-1</sup> )	7
3 Computed energies of H <sub>2</sub> Q-branch transitions	8
4 Computed energies of H <sub>2</sub> S-branch transitions	9

## FIGURES

1 H <sub>2</sub> CARS Q-branch spectra at 2500 K	11
2 H <sub>2</sub> CARS Q-branch spectra at 3000 K	11
3 Temperature variation of H <sub>2</sub> CARS spectra	12
4 H <sub>2</sub> CARS S-branch at 2732 K	13

## INTRODUCTION

The use of coherent anti-stokes Raman scattering (CARS) spectroscopy in combustion studies is well documented (refs 1 through 5). Hydrogen is a major combustion product of propellants, as illustrated by H<sub>2</sub> CARS S-branch transitions, obtained from both CH<sub>4</sub>/N<sub>2</sub>O model propellant flames and actual propellant flames (refs 6 and 7).

Because the use of H<sub>2</sub> CARS spectra to obtain temperature and concentration profiles is limited by the reliability of the spectroscopic constants, a literature search was conducted (refs 8 through 11) to find a suitable set of spectroscopic constants, and a set of ab initio calculations were obtained from Ermler.<sup>1</sup> The method used by Ermler is described briefly below. A more complete treatment is given in the literature (refs 12 through 15). Overall the transition energies calculated on the basis of Ermler's constants agreed most closely with our experimental results, so that particular set of spectroscopic constants was used to calculate H<sub>2</sub> S- and Q-branches.

## CARS THEORY

The observed CARS spectrum is proportional to the square of the modulus of the third order susceptibility,  $\chi^{(3)}$ , which is the sum of a resonant term  $\chi_r$ , and a nonresonant term  $\chi_{nr}$ , which are related to the vibrational and electronic displacement, respectively

$$\chi^{(3)} = \chi_r + \chi_{nr} \quad (1)$$

The resonant term is calculated as the sum of Lorentian line shapes of each rotational transition

$$\chi_r = \sum_j K_j \frac{\Gamma_j}{(2\Delta\omega_j - i\Gamma_j)} \quad (2)$$

given that

$$K_j = \frac{2N}{h} |\alpha_j|^2 (\Delta p_j^{(0)}) \Gamma_j^{-1} \quad (3)$$

where N is the number density,  $\alpha_j$  is the isotropic polarizability matrix element for the transition,  $\Delta p_j^{(0)}$  is the normalized population difference between the

---

<sup>1</sup> Personal communication between W. C. Ermler, Stevens Institute of Technology, Hoboken, NJ and J. Fendell, ARDC, May 1983.

molecular energy levels involved in the transition,  $\omega_j$  is the isolated pressure-broadened linewidth, and  $\Delta\omega_j = \omega_1 - \omega_2 - \omega_j$ . The calculated  $|\chi^{(3)}|^2$  is first convoluted over the laser shapes, then over a triangular slit function.

$\chi_r$  is the sum of real and imaginary components  $\chi'$  and  $\chi''$ , respectively, so that

$$|\chi^{(3)}|^2 = \chi'^2 + 2\chi'\chi_{nr} + \chi''^2 + \chi_{nr}^2 \quad (4)$$

$\chi'$  and  $\chi''$  display dispersive and resonant behavior with respect to the detuning frequency,  $\Delta\omega_j$ .

As the concentration of the resonant species is lowered, the cross term  $2\chi'\chi_{nr}$ , which is dispersive, influences the shape of the spectrum. The observation of dispersively modulated spectra allows temperature and concentration to be estimated on the basis of model calculations.

The concentration of various species from the ratio of the total CARS intensity to the nonresonant intensity at any frequency where resonant transition of the species occurs can also be estimated. In broadband CARS, the nonresonant susceptibility is usually observed directly from regions where no resonance occurs. The spectral distribution of the nonresonant susceptibility, which reflects that of  $\omega_2$ , can be obtained either from measurements of the distribution of  $\omega_2$  or directly from measurements of a nonresonant gas (ref 16).

## RESULTS

### Spectroscopic Constants

In an effort to find theoretical support for experimental observations, a literature search for spectroscopic constants for the  $X^1\Sigma^+$  state of hydrogen was conducted. Constants published by Stoicheff (ref 8), Fink et al. (ref 9), Herzberg (ref 10), and Huber and Herzberg (ref 11) were available in the literature. Another set was obtained by data reduction of the results obtained from Ermler.

In his calculations, Ermler used potential energy curves for the  $X^1\Sigma^+$  state of hydrogen calculated by Kolos and Wolniewicz (ref 13). These potential<sup>g</sup> curves are obtained by using a generalized James-Coolidge wavefunction with variational parameters in elliptic coordinates, which is then used to solve the Schrodinger equation by numerical methods. Double precision arithmetic using 15 vibrational and 15 rotational levels were used in the calculations.

### Application of Spectroscopic Constants

The total energy of a molecule is a function of both the rotational and vibrational quantum numbers. The expression is given as



$$E(v,J) = \omega_e(v + 0.5) - X_e \omega_e(v + 0.5)^2 + Y_e \omega_e(v + 0.5)^3 - Z_e \omega_e(v + 0.5)^4 + \\ B_v(J^2 + J) - D_v J^2(J + 1)^2 + H_v(J^3)(J + 1)^3$$

where

$$B_v = B_e + \alpha_e(v + 0.5) + \gamma_e(v + 0.5)^2$$

$$D_v = D_e + \beta_e(v + 0.5) + \delta_e(v + 0.5)^2$$

$$H_v = H_0 + H_1(v + 0.5) + H_2(v + 0.5)^2$$

It is useful to know the values of  $B_v$ ,  $D_v$ , and  $H_v$ , since they allow us to predict the frequencies at which pure rotational (S-branch) and ro-vibrational (Q-branch) transitions will occur.

$$\text{S-branch} = E(I,J+2) - E(I,J)$$

$$\text{Q-branch} = E(I+1,J) - E(I,J)$$

In general,  $B_v$ ,  $D_v$ , and  $H_v$  are approximated by second-order polynomials. Stoicheff, Herzberg, and Huber and Herzberg stated these polynomials explicitly, but Fink et al. and Ermler stated these quantities at various values of  $v$ . In order to use these values in a systematic way in calculating S-branch and Q-branch spectra, values of  $B_v$ ,  $D_v$ , and  $H_v$  corresponding to  $v = 0,1,2$  were fitted to a second-order polynomial. The estimated standard error for these correlations ranged between  $10^{-3}$  and  $10^{-18}$  for Fink's results and between  $10^{-11}$  and  $10^{-18}$  for Ermler's results. The values for  $B_v$ ,  $D_v$ , and  $H_v$  from all sources are compiled in table 1.

In table 2, the calculated S-branch frequencies are compared to our recently obtained experimental results. There is a clear difference among the results obtained by using various constants to calculate higher S-branch transitions. The constants of Fink et al. and Ermler were used to calculate the transition frequencies found in tables 3 and 4, since these particular sets of constants agreed most closely with experimental results.

#### Calculation of $H_2$ CARS S- and Q-Branches

$H_2$  CARS S- and Q-branches were calculated using Ermler's spectroscopic constants. The Q-branch results for various temperatures are given in figures 1, 2, and 3. The S-branch results shown in figure 4 for the  $S_0(7,5)^2$  transition at  $1815 \text{ cm}^{-1}$  illustrates conditions comparable to those in the  $\phi = 1.8 \text{ CH}_4/\text{N}_2\text{O}$  flame

---

<sup>2</sup> S-branch transitions are labeled using the notation  $S_v(J', J'')$ .

in which it was observed (refs 6 and 7). In these calculations, a Doppler broadened linewidth and a  $3.0 \text{ cm}^{-1}$  slit function were assumed.

## DISCUSSION

The recently observed higher S-branch transitions (refs 6 and 7) are compared to the transition frequencies given by various spectroscopic constants in table 2. In all cases, the constants of Fink et al. and Ermler agree more closely with experimental results than other constants. For the  $v = 0$  transitions, the results of Fink et al. and Ermler diverge as the transitions increase in frequency. Ermler's results are closer to the experimental results for  $S_0(9,7)$  than those of Fink et al. For  $S_0(11,9)$ , the difference between experimental results and those of Fink et al. is large enough to be experimentally discernible. The frequency of the  $S_0(11,9)$  transition has been observed experimentally at  $2131 \text{ cm}^{-1}$  by us (refs 6 and 7) as well as Farrow et al. (ref 17) in good agreement with Ermler's value of  $2130 \text{ cm}^{-1}$ . The results obtained for  $v = 1$  do not differ greatly for either set of constants until levels higher than the observed transitions are reached. On the basis of present experimental data, Ermler's constants agree most closely with the experiment.

For both  $v = 0$  and  $v = 1$ , Ermler's constants predict that the Q-branch transitions will be more closely spaced than the results of Fink et al. As seen from the computed results (table 3), Ermler's constants predict experimentally discernable differences from those at Fink et al. (ref 18) beginning at  $J''=6$ . The computed CARS Q-branch spectra (fig. 1 and 1a) show that above 2500 K, Q-branches above  $J''=6$  are significantly populated. Q-branch spectra will be taken to confirm the validity of the spectroscopic constants at these temperatures.

The results obtained indicate that the set of spectroscopic constants obtained from the ab initio calculations are in better agreement with experimental results than other sets of constants.

## REFERENCES

1. R. L. Farrow, P. L. Mattern, and L. A. Rahn, Applied Optics, vol 21, 1982, p 3119.
2. R. J. Hall and A. C. Eckbreth, Optical Engineer, vol 20, 1981, p 494.
3. S. Druet and J. P. Taran, Chemical and Biological Applications of Lasers, C. B. Moore, ed, Academic Press, New York, NY, 1979.
4. J. W. Nibler and G. V. Knighten, Raman Spectroscopy of Gases and Liquids, A. Weber, ed, Springer-Verlag, New York, NY, 1979.
5. L. E. Harris, "CARS Spectroscopy of Propellant Flames," Proceedings of the 9th International Colloquium on Dynamics of Explosives and Reactives Systems, Poitiers, France, 1983.
6. L. E. Harris, K. Aron, J. Fendell, 19th JANNAF Combustion Meeting, Greenbelt, MD, 1982.
7. K. Aron, L. E. Harris, J. Fendell, Applied Optics, to be published.
8. B. P. Stoicheff, Raman Spectroscopy of Gases, vol IX, 1957.
9. U. Fink et al., J. Mol Spect, vol 18, 1965, p 384.
10. G. Herzberg, Spectra of Diatomic Molecules, Van Nostrand, New York, NY, 1950.
11. K. P. Huber and G. Herzberg, Constants of Diatomic Molecules, Van Nostrand, New York, NY, 1979.
12. W. Kolos and L. Wolniewicz, J. of Chemical Physics, vol 43, 1965, p 2429.
13. J. W. Cooley, Math Computations, vol 15, 1961, p 363.
14. W. Kolos and L. Wolniewicz, J. of Chemical Physics, vol 49, 1968, p 404.
15. W. Kolos and L. Wolniewicz, J. of Chemical Physics, vol 41, 1974, p 3663.
16. L. E. Harris, Combustion and Flame, vol 53, pp 103-121, 1983.  
L. E. Harris, Chemical Physics Letters, vol 93, 1982, p 335.
17. R. Farrow, P. Mattern, and L. A. Rahn, 7th International Raman Conference, Ottawa, Ontario, Canada, 1980, p 668.
18. K. Aron and L. E. Harris, 20th JANNAF Combustion Meeting, Monterey, CA, 1983.

Table 1. Comparison of spectroscopic constants ( $\text{cm}^{-1}$ )

<u>Constants</u>	<u>Herzberg</u>	<u>Huber and Herzberg</u>	<u>Stoicheff</u>	<u>Fink et al.</u>	<u>Ermler</u>
Be	60.800	60.853	60.840	60.8318	60.7922
$\alpha_e$	-2.993	-3.062	-3.0177	-3.0087	-3.0320
$\beta_e$	0.025	0.057	0.0285	0.0266	0.0350
De	0.0464	0.00471	0.04684	0.0471	0.0448
Be	-0.00134	-0.0027	-0.0017	-0.0029	-0.0016
$\delta_e$	--	0.0004	$3 \times 10^{-5}$	$4.5 \times 10^{-4}$	$4.5 \times 10^{-5}$
$H_0$	$5.18 \times 10^{-5}$	--	$5.2 \times 10^{-5}$	$5.62 \times 10^{-6}$	$3.23 \times 10^{-5}$
$H_1$	--	--	--	$-1.7 \times 10^{-6}$	$-8.70 \times 10^{-7}$
$H_2$	--	--	--	$4 \times 10^{-7}$	$-2.50 \times 10^{-8}$
$\omega_e$	4395.2	4401.21	4401.21	4401.217	4400.39
$x_e \omega_e$	117.90	121.33	121.43	121.343	120.814
$y_e \omega_e$	0.29	0.812	0.892	0.8145	0.7241
$z_e \omega_e$	0.	0.	0.	0.	0.

Table 2. Calculation of selected transitions ( $\text{cm}^{-1}$ )

<u>Transition<sup>a</sup></u>	<u>Experimental<sup>b</sup></u>	<u>Stoicheff</u>	<u>Fink et al.</u>	<u>Ermler</u>	<u>Huber and Herzberg</u>
$S_0(7,5)$	1446	1447.67	1447.61	1447.80	1449.83
$S_0(9,7)$	1809	1817.95	1817.18	1815.08	1822.05
$S_0(11,9)$	2131	2145.01	2141.91	2130.32	2150.30
$S_1(9,7)$	1721	1725.42	1719.90	1721.81	1723.13
$S_1(11,9)$	2020	2035.96	2019.02	2019.83	2032.29

<sup>a</sup> The transitions are labeled " $S_v(J',J'')$ ."

<sup>b</sup> The experimental data were taken from CARS data given in refs 7 and 18.

Table 3. Computed energies of H<sub>2</sub> Q-branch transitions

J	V = 0		V = 1	
	<u>Fink et al.</u>	<u>Ermler</u>	<u>Fink et al.</u>	<u>Ermler</u>
0	4161.18	4161.12	3925.82	3927.00
1	4155.25	4155.20	3919.99	3920.23
2	4143.32	4143.40	3908.16	3908.71
3	4125.21	4125.79	3890.00	3891.52
4	4100.68	4102.49	3865.00	3868.80
5	4069.40	4073.65	3832.52	3840.61
6	4030.94	4039.43	3791.70	3807.21
7	3984.82	4000.08	3741.56	3768.80
8	3930.44	3955.85	3680.93	3725.63
9	3867.15	3907.04	3608.47	3677.99
10	3794.19	3853.97	3522.70	3626.20
11	3710.74	3797.03	3421.95	3570.64
12	3615.89	3736.61	3304.38	3511.69
13	3508.63	3673.17	3168.01	3449.80
14	3387.88	3607.17	3010.67	3385.44
15	3252.49	3539.16	2830.03	3319.12
16	3101.21	3469.66	2623.60	3251.37
17	2932.70	3399.29	2388.70	3182.80
18	2745.56	3328.67	2122.53	3113.99
19	2538.28	3258.47	1822.07	3045.63
20	2309.30	3189.39	1484.18	2978.39

Table 4. Computed energies of H<sub>2</sub> S-branch transitions

<u>J'</u>	<u>J''</u>	<u>V = 0</u>		<u>V = 1</u>	
		<u>Fink et al.</u>	<u>Ermler</u>	<u>Fink et al.</u>	<u>Ermler</u>
0	0	354.37	354.13	336.69	336.41
3	1	587.02	586.74	557.68	557.33
4	2	814.40	814.22	773.55	773.30
5	3	1034.65	1034.67	982.47	982.50
6	4	1246.16	1246.37	1182.79	1183.26
7	5	1447.61	1447.80	1373.12	1374.15
8	6	1638.11	1637.69	1552.39	1553.96
9	7	1817.18	1815.08	1719.90	1721.81
10	8	1984.89	1979.37	1875.37	1877.15
11	9	2141.91	2130.32	2019.02	2019.83
12	10	2289.56	2268.18	2151.61	2150.14
13	11	2429.91	2393.64	2274.49	2268.85
14	12	2565.84	2507.95	2389.67	2377.27
15	13	2701.09	2612.97	2499.89	2477.29
16	14	2840.35	2711.12	2608.65	2571.43
17	15	2989.33	2805.54	2720.27	2662.86
18	16	3154.84	2900.08	2839.97	2755.49
19	17	3344.84	2999.35	2973.92	2853.99
20	18	3568.49	3108.80	3129.26	2963.83
21	19	3836.30	3234.71	3314.22	3091.35

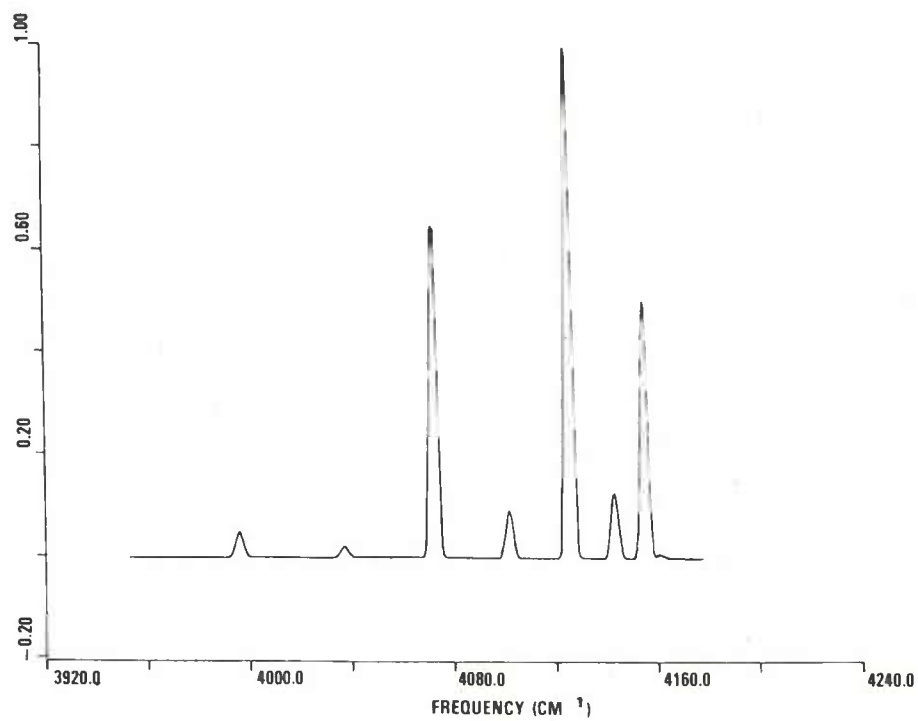


Figure 1. H<sub>2</sub> CARS Q-branch spectra at 2500 K

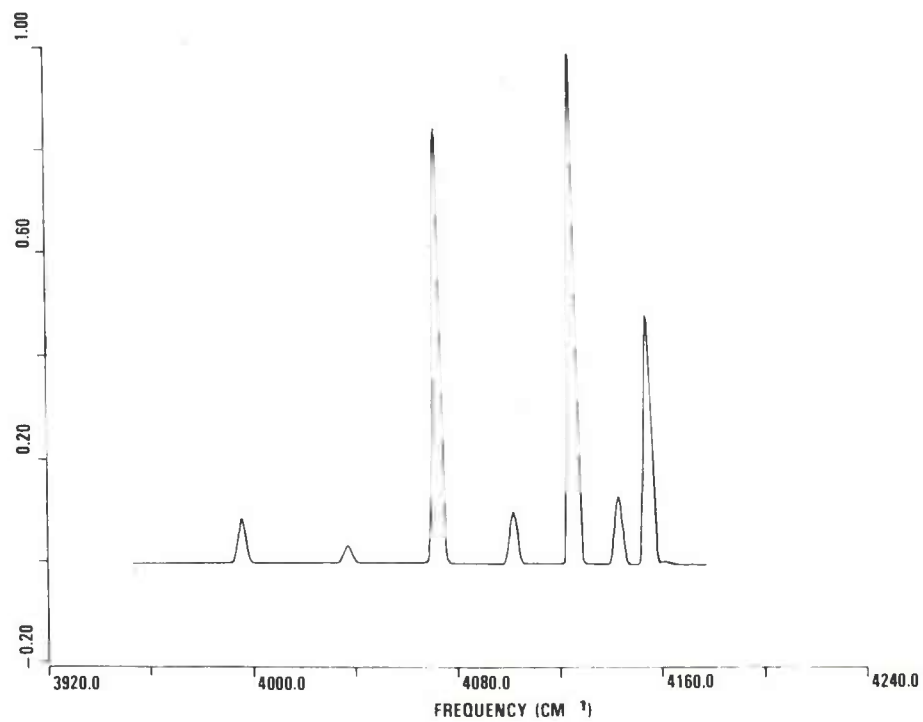


Figure 2. H<sub>2</sub> CARS Q-branch spectra at 3000 K

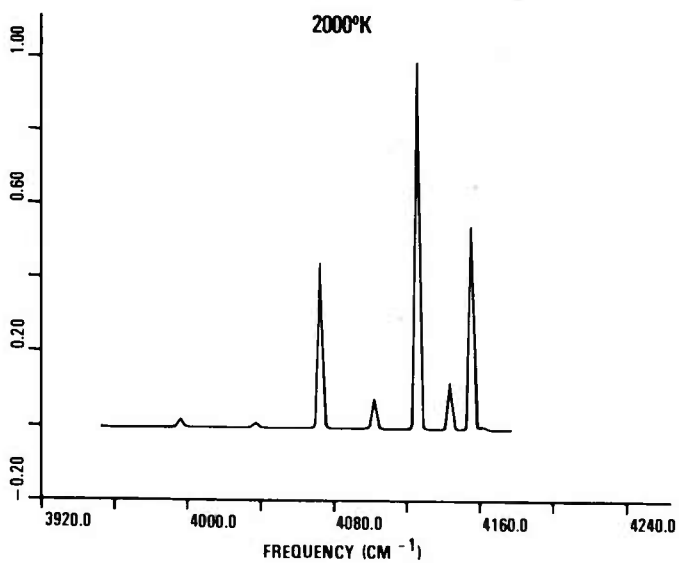
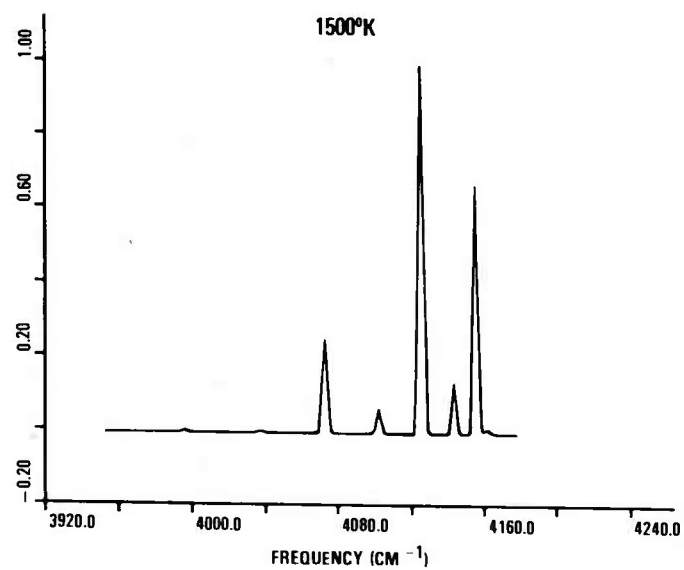
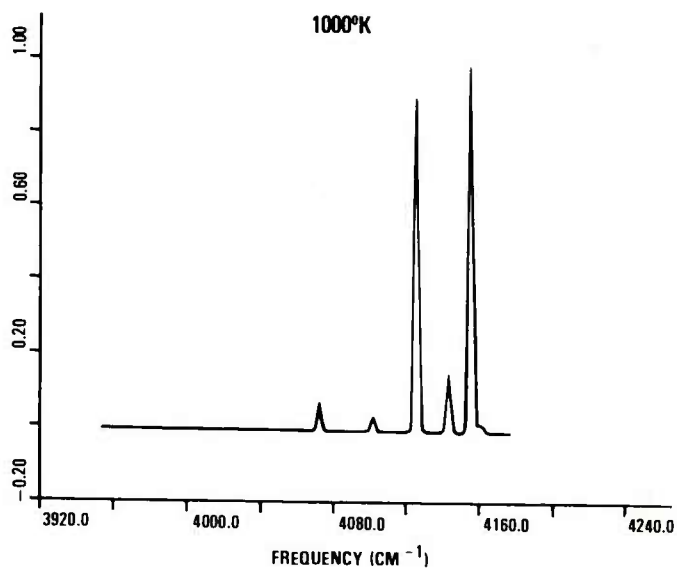
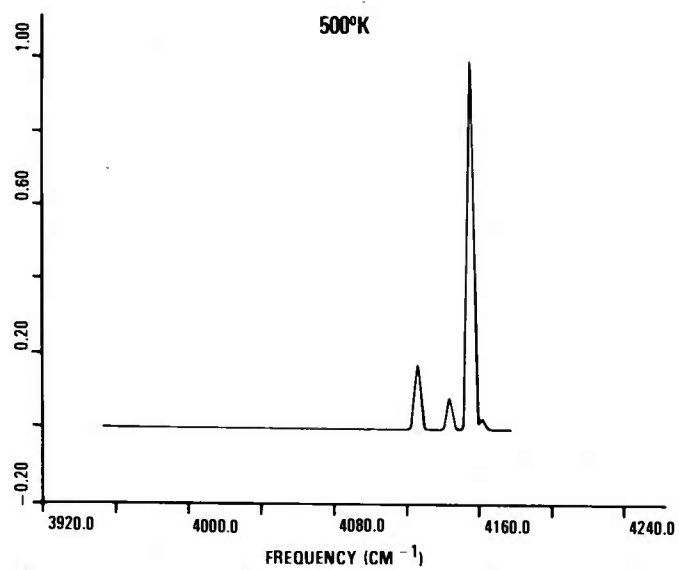


Figure 3. Temperature variation of H<sub>2</sub> CARS spectra



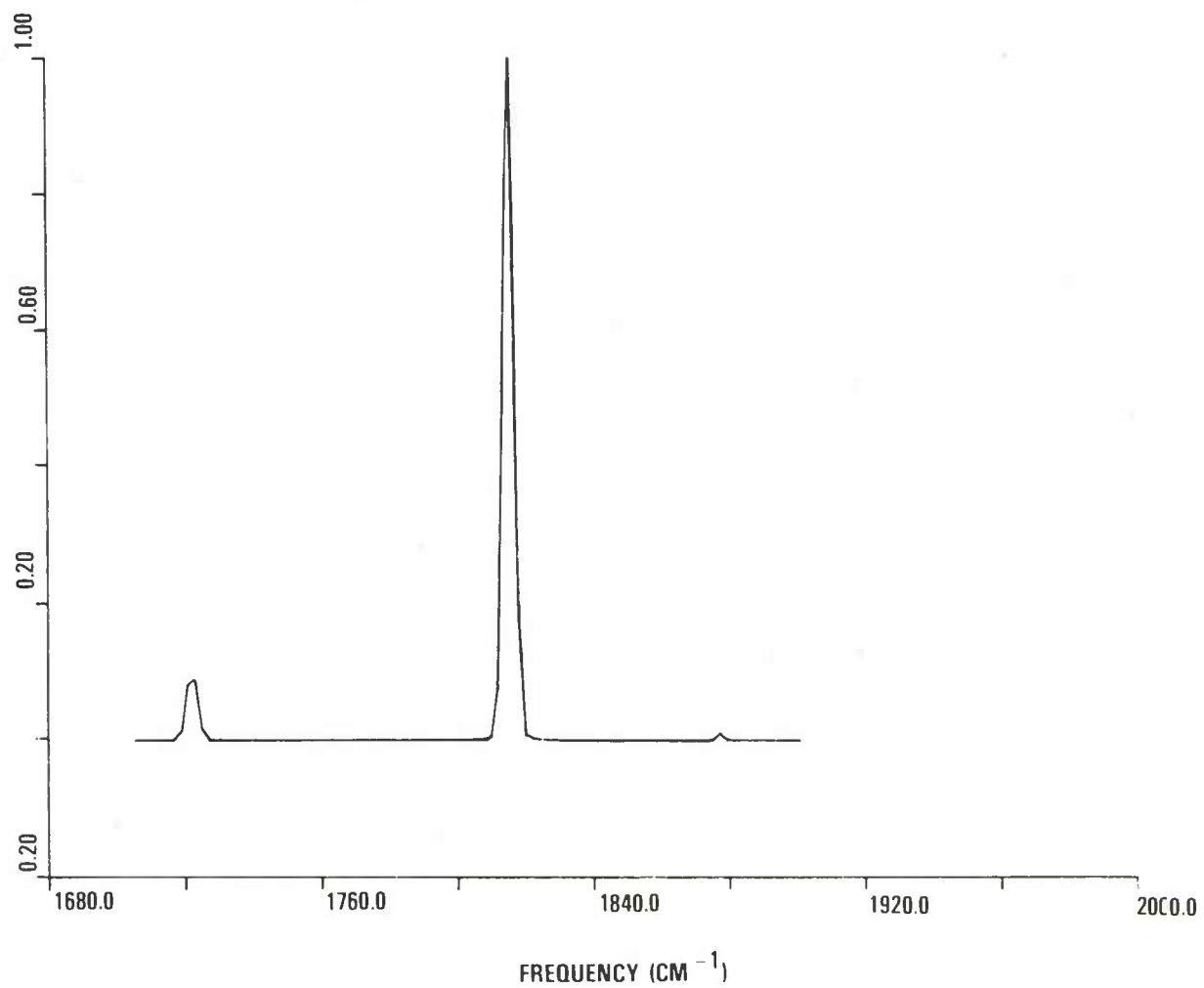


Figure 4. H<sub>2</sub> CARS S-branch at 2732 K

## DISTRIBUTION LIST

Commander  
Armament Research and Development Center  
U.S. Army Armament, Munitions and  
Chemical Command

ATTN: DRSMC-TSS(D) (5)  
DRSMC-TDC(D), D. A. Gyorog  
DRSMC-GCL(D)  
DRSMC-LC(D), J. Frasier  
J. P. Picard  
DRSMC-LCA(D), T. Davidson  
DRSMC-LCA-G(D), J. Lannon  
D. Downs  
L. Harris (10)  
T. Vladimiroff  
A. Beardell  
Y. Carignon  
J. Fendell (10)  
K. Aron  
E. Petrow  
DRSMC-LCE(D), R. Walker  
P. Marinkas  
C. Capellos  
F. Owens  
S. Bulusu  
F. Gilbert

Dover, NJ 07801

Administrator  
Defense Technical Information Center  
ATTN: Accessions Division (12)  
Cameron Station  
Alexandria, VA 22314

Director  
U.S. Army Materiel Systems  
Analysis Activity  
ATTN: DRXSY-MP  
Aberdeen Proving Ground, MD 21005

Commander  
Chemical Research and Development Center  
U.S. Army Armament, Munitions and  
Chemical Command  
ATTN: DRSMC-CLJ-L(A)  
DRSMC-CLB-PA(A)  
APG, Edgewood Area, MD 21010

Director  
Ballistics Research Laboratory  
Armament Research and Development Center  
U.S. Army Armament, Munitions and  
Chemical Command

ATTN: DRSMC-TSB-S(A)  
DRSMC-BLP(A), L. Watermier  
A. Barrows  
G. Adams  
R. Fifer  
M. Miller  
T. Coffee  
J. Heimeryl  
C. Nelson  
J. Vanderhoff  
J. Anderson

Aberdeen Proving Ground, MD 21005

Chief  
Benet Weapons Laboratory, LCWSL  
Armament Research and Development Center  
U.S. Army Armament, Munitions and  
Chemical Command  
ATTN: DRSMC-LCB-TL  
Watervliet, NY 12189

Commander  
U.S. Army Armament, Munitions and  
Chemical Command  
ATTN: DRSMC-LEP-L(R)  
Rock Island, IL 61299

Director  
U.S. Army TRADOC Systems  
Analysis Activity  
ATTN: ATAA-SL  
White Sands Missile Range, NM 88002

Director  
Defense Advanced Research Projects  
Agency  
ATTN: LTC C. Buck  
1400 Wilson Boulevard  
Arlington, VA 22209

Commander  
U.S. Army Materiel Development  
and Readiness Command  
ATTN: DRCMD-ST  
5001 Eisenhower Avenue  
Alexandria, VA 22333

Commander  
U.S. Army Watervliet Arsenal  
ATTN: SARWV-RD, R. Thierry  
Watervliet, NY 12189

Director  
U.S. Army Air Mobility Research  
and Development Laboratory  
Ames Research Center  
Moffett Field, CA 94035

Commander  
U.S. Army Communications Research  
and Development Command  
ATTN: DRDCO-PPA-SA  
Fort Monmouth, NJ 07703

Commander  
U.S. Army Electronics Research  
and Development Command  
Technical Support Activity  
ATTN: DELSD-L  
Fort Monmouth, NJ 07703

Commander  
U.S. Army Missile Command  
ATTN: DRSMI-R  
DRSMI-YDL  
Redstone Arsenal, AL 35809

Commander  
U.S. Army Natick Research  
and Development Command  
ATTN: DRXRE, D. Sieling  
Natick, MA 01762

Commander  
U.S. Army Tank Automotive Research  
and Development Command  
ATTN: DRDTA-UL  
Warren, MI 48090

Commander  
U.S. Army White Sands Missile Range  
ATTN: STEWS-VT  
White Sands Missile Range, NM 88002

Commander  
U.S. Army Materials and  
Mechanics Research Center  
ATTN: DRXMR-ATL  
Watertown, MA 02172

Commander  
U.S. Army Research Office  
ATTN: Technical Library  
D. Squire  
F. Schmiedeshaff  
R. Ghirardelli  
M. Ciftan  
P.O. Box 12211  
Research Triangle Park, NC 27706

Office of Naval Research  
ATTN: Code 473  
G. Neece  
800 N. Quincy Street  
Arlington, VA 22217

Commander  
Naval Sea Systems Command  
ATTN: J. W. Murrin, SEA-62R2  
National Center  
Bldg 2, Room 6E08  
Washington, DC 20362

Commander  
Naval Surface Weapons Center  
ATTN: Library Branch, DX-21  
Dahlgren, VA 22448

Commander  
Naval Surface Weapons Center  
ATTN: Code 240, S. J. Jacobs, J. Sharma  
Code 730  
Silver Spring, MD 20910

Commander  
Naval Underwater Systems Center  
Energy Conversion Department  
ATTN: Code 5B331, R. S. Lazar  
Newport, RI 02840

Commander  
Naval Weapons Center  
ATTN: R. Derr  
C. Thelen  
China Lake, CA 93555

Commander  
Naval Research Laboratory  
ATTN: Code 6180  
Washington, DC 20375

Superintendent  
Naval Postgraduate School  
ATTN: Technical Library  
D. Netzer  
A. Fuhs  
Monterey, CA 93940

Commander  
Naval Ordnance Station  
ATTN: Dr. Charles Dale  
Technical Library  
Indian Head, MD 20640

AFOSR  
ATTN: J. F. Masi  
B. T. Wolfson  
D. Ball  
L. Caveny  
Bolling AFB, DC 20332

AFRPL (DYSC)  
ATTN: D. George  
J. N. Levine  
Edwards AFB, CA 93523

National Bureau of Standards  
ATTN: J. Hastie  
T. Kashiwagi  
H. Semerjian  
M. Jacox  
K. Smyth  
J. Stevenson  
Washington, DC 20234

Lockheed Palo Alto Research Laboratories  
ATTN: Technical Information Center  
3521 Hanover Street  
Palo Alto, CA 94304

Aerojet Solid Propulsion Co.  
ATTN: P. Micheli  
Sacramento, CA 95813

ARO Incorporated  
ATTN: N. Dougherty  
Arnold AFS, TN 37389

Atlantic Research Corporation  
ATTN: M. K. King  
5390 Cherokee Avenue  
Alexandria, VA 22314

AVCO Corporation  
AVCO Everett Research Laboratory  
Division  
ATTN: D. Stickler  
2385 Revere Beach Parkway  
Everett, MA 02149

Calspan Corporation  
ATTN: E. B. Fisher  
A. P. Trippe  
P.O. Box 400  
Buffalo, NY 14221

Foster Miller Associates, Inc.  
ATTN: A. J. Erickson  
135 Second Avenue  
Waltham, MA 02154

General Electric Company  
Armament Department  
ATTN: M. J. Bulman  
Lakeside Avenue  
Burlington, VT 05402

General Electric Company  
Flight Propulsion Division  
ATTN: Technical Library  
Cincinnati, OH 45215

Hercules Incorporated  
Alleghany Ballistic Lab  
ATTN: R. Miller  
Technical Library  
Cumberland, MD 21501

Hercules Incorporated  
Bacchus Works  
ATTN: B. Isom  
Magna, UT 84044

IITRI  
ATTN: M. J. Klein  
10 West 35th Street  
Chicago, IL 60615

Olin Corporation  
Badger Army Ammunition Plant  
ATTN: J. Ramnarace  
Baraboo, WI 53913

Olin Corporation  
New Haven Plant  
ATTN: R. L. Cook  
D. W. Riefler  
275 Winchester Avenue  
New Haven, CT 06504

Paul Gough Associates, Inc.  
ATTN: P. S. Gough  
P.O. Box 1614  
Portsmouth, NH 03801

Physics International Company  
2700 Merced Street  
Leandro, CA 94577

Pulsepower Systems, Inc.  
ATTN: L. C. Elmore  
815 American Street  
San Carlos, CA 94070

Rockwell International Corp.  
Rocketdyne Division  
ATTN: C. Obert  
J. E. Flanagan  
A. Axeworthy  
6633 Canoga Avenue  
Canoga Park, CA 91304

Rockwell International Corp.  
Rocketdyne Division  
ATTN: W. Haymes  
Technical Library  
McGregor, TX 76657

Science Applications, Inc.  
ATTN: R. B. Edelman  
Combustion Dynamics and  
Propulsion Division  
23146 Cumorah Crest  
Woodland Hills, CA 91364

Shock Hydrodynamics, Inc.  
ATTN: W. H. Anderson  
4710-16 Vineland Avenue  
N. Hollywood, CA 91602

Thiokol Corporation  
Elkton Division  
ATTN: E. Sutton  
Elkton, MD 21921



Thiokol Corporation  
Huntsville Division  
ATTN: D. Flanigan  
R. Glick  
Technical Library  
Huntsville, AL 35807

Thiokol Corporation  
Wasatch Division  
ATTN: J. Peterson  
Technical Library  
P.O. Box 524  
Brigham City, UT 84302

TRW Systems Group  
ATTN: H. Korman  
One Space Park  
Redondo Beach, CA 90278

United Technologies  
Chemical Systems Division  
ATTN: R. Brown  
Technical Library  
P.O. Box 358  
Sunnyvale, CA 94086

Battelle Memorial Institute  
ATTN: Technical Library  
R. Bartlett  
505 King Avenue  
Columbus, OH 43201

Brigham Young University  
Department of Chemical Engineering  
ATTN: M. W. Beckstead  
Provo, UT 84601

California Institute of Technology  
204 Karmar Lab  
Mail Stop 301-46  
ATTN: F. E. C. Culick  
1201 E. California Street  
Pasadena, CA 91125

Case Western Reserve University  
Division of Aerospace Sciences  
ATTN: J. Tien  
Cleveland, OH 44135

Georgia Institute of Technology  
School of Aerospace Engineering  
ATTN: B. T. Zinn  
E. Price  
W. C. Strahle  
Atlanta, GA 30332

Institute of Gas Technology  
ATTN: D. Gidaspow  
3424 S. State Street  
Chicago, IL 60616

Johns Hopkins University/APL  
Chemical Propulsion Information Agency  
ATTN: T. Christian  
Johns Hopkins Road  
Laurel, MD 20810

Massachusetts Institute of Technology  
Department of Mechanical Engineering  
ATTN: T. Toong  
Cambridge, MA 02139

Pennsylvania State University  
Applied Research Laboratory  
ATTN: G. M. Faeth  
P.O. Box 30  
State College, PA 16801

Pennsylvania State University  
Department of Mechanical Engineering  
ATTN: K. Kuo  
University Park, PA 16801

Pennsylvania State University  
Department of Material Sciences  
ATTN: H. Palmer  
University Park, PA 16801

Princeton Combustion Research  
Laboratories  
ATTN: M. Summerfield  
N. Messina  
1041 U.S. Highway One North  
Princeton, NJ 08540

Princeton University  
Forrestal Campus  
ATTN: I. Glassman  
F. Dryer  
Technical Library  
P.O. Box 710  
Princeton, NJ 08540

Purdue University  
School of Mechanical Engineering  
ATTN: J. Osborn  
S. N. B. Murthy  
N. M. Laurendeau  
TSPC Chaffee Hall  
W. Lafayette, IN 47906

Rutgers State University  
Department of Mechanical and  
Aerospace Engineering  
ATTN: S. Temkin  
University Heights Campus  
New Brunswick, NJ 08903

SRI International  
ATTN: Technical Library  
D. Crosley  
J. Barker  
D. Golden  
333 Ravenswood Avenue  
Menlo Park, CA 94025

Stevens Institute of Technology  
W. C. Ermler  
Department of Chemistry and Chemical Engineering  
Hoboken, NJ 07030

United Technology  
ATTN: Alan Ecbreth  
Robert Hall  
Research Center  
East Hartford, CT 06108

Commander  
Naval Research Laboratory  
Chemistry Division  
ATTN: A. Harvey  
Washington, DC 20375

General Motors Research Laboratory  
ATTN: J. H. Bechtel  
Warren, Michigan 48090

System Research Laboratory  
ATTN: L. Goss  
2600 Indian Ripple Rd  
Dayton, Ohio 45440

Exxon Research and Engineering  
ATTN: A. Dean  
M. Chou  
P.O. Box 45  
Linden, NJ 07036

Ford Motor Company  
Research Staff  
ATTN: K. Marko  
L. Rimai  
Dearborn, Michigan 48120

Sandia Laboratories  
Applied Physics Division I  
ATTN: L. Rahn  
D. Stephenson  
Livermore, CA 94550

Rensselaer Polytechnic Institute  
Dept. of Chem. Engineering  
ATTN: A. Fontijn  
Troy, NY 12181

University of California,  
San Diego  
Ames Department  
ATTN: F. Williams  
P.O. Box 109  
La Jolla, CA 92037

University of California  
Dept. of Mechanical Eng.  
ATTN: J. W. Daily  
Berkeley, CA 94720

University of Dayton  
University of Dayton Research Inst.  
Dayton, OH 45406

University of Florida  
Dept. of Chemistry  
ATTN: J. Winefordner  
Gainesville, Florida 32601

University of Illinois  
Dept. of Mechanical Eng.  
ATTN: H. Krier  
144 MEB, 1206 W. Green St.  
Urbana, IL 61801

University of Minnesota  
Dept. of Mechanical Eng.  
ATTN: E. Fletcher  
Minneapolis, MN 55455

University of California,  
Santa Barbara  
Quantum Institute  
ATTN: K. Schofield  
M. Steinberg  
Santa Barbara, CA 93106

University of Southern California  
Department of Chemistry  
ATTN: S. Benson  
Los Angeles, CA 90007

Stanford University  
Department of Mech. Eng.  
ATTN: R. Hanson  
Stanford, CA 93106

University of Texas  
Department of Chemistry  
ATTN: W. Gardiner  
H. Schaefer  
Austin, TX 78712

University of Utah  
Dept. of Chemical Engineering  
ATTN: A. Baer  
G. Flandro  
Salt Lake City, UT 84112